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E687

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Abstract

Charged hadronic four-body decays of D^0 mesons have been studied in the E687 photoproduction experiment at Fermilab. Branching ratios relative to the $D^0 \to K^-\pi^+\pi^+\pi^-$ decay mode for the Cabibbo-suppressed decays $D^0 \to \pi^-\pi^+\pi^-\pi^+$, $D^0 \to K^-K^+\pi^-\pi^+$ have been measured and the first evidence of the $D^0 \to K^-K^+K^-\pi^+$ decay mode is reported. An analysis of the $D^0 \to K^-K^+\pi^-\pi^+$ resonance structure is also presented.

Hadronic decays of charm mesons have been extensively studied in recent years. While several experimental measurements are now available, the theoretical predictions are limited mainly to two-body decay modes [1] [2] [3]. The hadronic processes are difficult to calculate because of gluon exchange among the quarks in the initial and final states and final state interactions (FSI). Although D meson decays are dominated by two-body modes, it is worthwhile to complete the experimental picture of the charm meson decays with the study of the multi-body modes.

In this letter we present results from D^0 decays into four charged particles. In particular the most accurate determination for the branching ratios of two Cabibbo-suppressed decays, $D^0 \rightarrow \pi^-\pi^+\pi^-\pi^+$ and $D^0 \rightarrow K^-K^+\pi^-\pi^+$ is presented and the first evidence of the decay mode $D^0 \rightarrow K^-K^+K^-\pi^+$ is reported (throughout this paper the charge conjugate state is implied). These modes may be produced as non-resonant final states or via two-body and three-body intermediate resonant states. A study of the $D^0 \rightarrow K^-K^+\pi^-\pi^+$ resonance structure, treated as an incoherent superposition of resonances, is presented.

This analysis is based on data collected during the 1990-1991 fixed target run at Fermilab with the E687 spectrometer which is described in detail elsewhere [4]. A Bremsstrahlung photon beam of mean energy approximately $200\,GeV$ impinges on a 4cm Be target; particles from the interaction are detected in a large aperture magnetic spectrometer with excellent vertex measurement, particle identification and calorimetric capabilities. Kaons and pions in the D^0 final states are well separated in the momentum range $4.5 - 61\,GeV/c$ using three multicell Čerenkov counters. D^0 primary (production) and secondary (decay) vertices are resolved by means of a high resolution vertex detector consisting of 12 microstrip planes. The resolution in the transverse plane is approximately $9\,\mu m$ in the target region.

The four-body D^0 final states are selected using a *candidate driven vertex algorithm* [4]. A secondary vertex is formed from the four reconstructed tracks and the momentum vector of the D^0 candidate is used as a seed to intersect the other tracks in the event to find the primary vertex. Once the production and decay vertices are determined, the distance ℓ between them and the relative error σ_ℓ are computed. Cuts on the ℓ/σ_ℓ ratio are applied to extract the D^0 signals from the background. The topological configuration of the event is tested in four ways: the primary and secondary vertex confidence levels (minimum values of 1% were required) and two measures of vertex isolation, a *no point-back isolation* and a *secondary vertex isolation.* The *no point-back isolation* cut required that the maximum confidence level for a candidate D^0 daughter track to form a vertex with the tracks from the primary vertex was less than 30%. The *secondary vertex isolation* cut required that the maximum confidence level for another track to form a vertex with the D candidate be less than 0.01%. The three modes reported here and the normalization mode all have four charged tracks in the final state. The analyses differ mainly in the way the particle identification is handled, and less importantly in the way the isolation cuts are applied. While the acceptances of these states differ slightly, the use of the $D^0 \to K^-\pi^+\pi^+\pi^-$ final state as the normalization causes many systematic errors to cancel.

In the $D^0 \to \pi^-\pi^+\pi^-\pi^+$ analysis, only the four track combinations satisfying loose pion identification requirements (i.e. no pions are identified as either kaons or protons by the Čerenkov system) are kept. Suitable vertex cuts are then applied to reduce the large combinatorial background. In particular, we increase the minimum primary and secondary vertex confidence level cuts to 2% which better rejects pure combinatorial vertices. With a detachment cut of 7 ($\ell/\sigma_\ell \geq 7$) we obtain the invariant mass plot shown in Fig.1a. The peak at $1.75\,GeV/c^2$ is due to the reflection of the $D^0 \to K^-\pi^+\pi^+\pi^-$ mode when the kaon is misidentified as a pion by the Čerenkov system. A Monte Carlo simulation of this reflection reproduces the shape observed in the data. The 4π invariant mass distribution is fitted with a Gaussian for the signal, a Gaussian for the reflection structure and a second degree polynomial for the background. Possible contamination due to other charm hadron decays involving either an additional π^0 or charged pions outside the spectrometer acceptance would affect only the low mass region which we therefore exclude from the fit. A signal of 814 ± 52 $D^0 \to \pi^-\pi^+\pi^-\pi^+$ events is determined by a maximum likelihood fit.

In the $D^0 \to K^-K^+\pi^-\pi^+$ decay the joint requirement of two kaons in the final state reduces the background and allows us to use very loose Čerenkov cuts on the kaon candidates: kaon definite, kaon/pion ambiguous, kaon/proton ambiguous and even proton definite are accepted in the analysis. The fraction of events falling into each of these particle identification classes was reproduced by our Monte Carlo simulation. In the vertexing analysis the *no point-back isolation* cut is inefficient because the small Q value of the reaction results in smaller opening angles of the tracks in the laboratory frame. Candidate tracks coming from the vertex tend to point back to the primary, so that a considerable fraction of good events would be rejected by the *no point-back isolation* cut. The invariant mass plot for $K^-K^+\pi^+\pi^-$ combinations satisfying $\ell/\sigma_\ell \geq 7$ is shown in Fig.1b. The reflection from the $D^0 \to K^-\pi^+\pi^+\pi^-$ decays affects the high mass region. A maximum likelihood fit using a Gaussian for the signal, a second Gaussian for the reflection peak and a second degree polynomial for the background gives 244 ± 26 events.

The $D^0 \to K^-K^+K^-\pi^+$ decay mode is Cabibbo-allowed but is strongly suppressed by its small Q value and by the low probability of creating a $s\bar{s}$ couple. For this final state the background is considerably reduced because of the small phase space. The kaon tracks were required to satisfy the same identification criteria as those in the $D^0 \to K^-K^+\pi^+\pi^-$ analysis, and the same vertex requirements were used except the detachment cut which was $\ell/\sigma_\ell \geq 6$. The mass distribution shown in Fig.1c is fitted with a Gaussian for the signal and a second degree polynomial for the background. A maximum likelihood fit gives 20 ± 5 $D^0 \to K^-K^+K^-\pi^+$ events. In the fit procedure the D^0 mass is fixed to the world average [6] and the width to that obtained from a Monte Carlo simulation, to avoid fluctuations due to the low statistics. This result, which is conservatively a 4σ evidence, is the first observation of this decay mode.

Branching ratios of these modes relative to $D^0 \to K^-\pi^+\pi^+\pi^-$ have been measured. To minimize systematic effects the normalizing decay mode is selected using the same vertexing cuts of the considered mode. Our final measurements have been tested by modifying each of the vertex cuts individually; the results were always consistent within the errors. The invariant mass distribution for $K^-\pi^+\pi^+\pi^-$ candidates satisfying the vertex cuts used for the $D^0 \to K^-K^+\pi^+\pi^-$ analysis is shown in Fig.1d. The efficiency* corrected yields lead to the

*The efficiency for $D^0 \to K^-K^+\pi^+\pi^-$ was calculated assuming the final state is composed of a mixture of intermediate decay modes determined by our resonant analysis which follows; when the PDG [6] mixtures were assumed, the change in the relative branching ratio was well within the branching ratio measurements reported in Table I. Our new results are in good agreement with the previous determinations of the relative branching ratios and considerably increase the precision of the measurements.

The systematic errors on these measurements reflect uncertainties in reconstruction efficiency, Čerenkov particle identification and hadronic absorption of secondaries in the target and spectrometer materials. The estimates were obtained by splitting our data into disjoint samples depending on the D^0 momentum and the different periods in which the data were collected. The *S-factor method* from the Particle Data Group [7] was used to separate true systematic variations from statistical fluctuations. The branching ratio is evaluated for each of the statistically independent subsamples and a *scaled variance* is calculated; the *split sample* variance is defined as the difference between the reported statistical variance and the scaled variance if the scaled variance exceeds the statistical variance. The evaluation of systematic effects related to different fit procedures is performed on the whole sample. The branching ratios are calculated varying the fit conditions[†] and the sample variance is used because the fit variants are all a priori likely. The *split sample* variance and the variance from the different fitting procedures are then added to obtain the systematic error.

The reported measurements of the four-body decays of the D^0 meson are inclusive measurements. The resonant substructure in the decay $D^0 \to K^-K^+\pi^-\pi^+$, which has been studied by previous experiments [8] [9] [10], is of considerable interest since several theoretical models [1] [2] [3] make predictions for the resonant D decays, including the $D \to VV$ modes. Moreover the $D^0 \to \overline{K^{*0}}K^{*0}$ cannot occur through the simple spectator decay diagram and the W-exchange diagram is suppressed by the Glashow-Iliopoulos-Maiani (GIM) mechanism. Therefore an observation of this mode would be an indication of FSI.

We use a simplified approach to fit the resonant substructure in the decay $D^0 \to$

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statistical error.

[†]These include the choice of the estimator, the background shape and the Gaussian parameters.

$K^-K^+\pi^-\pi^+$ which assumes that the final state is the result of an incoherent superposition of decay modes containing the common lowest mass (K^-K^+), $(\pi^-\pi^+)$ and $(K^-\pi^+)$ resonances plus a four-body nonresonant channel: $\phi\pi^+\pi^-$ 3-body, $\phi\rho^0$, $K^-K^+\rho^0$ 3-body, $\overline{K^{*0}}K^+\pi^-$ 3-body, $K^{*0}K^-\pi^+$ 3-body, $\overline{K^{*0}}K^{*0}$ and $(K^-K^+\pi^-\pi^+)_{NR}$.

We extract the acceptance corrected event yield into each decay mode using a weighting technique where each event is weighted according to the values taken by specific two-body submasses in the four-body final state. The weights are obtained using information from separate Monte Carlo simulations for each of the 7 decay modes and the formalism of a linear fit which we now discuss. The acceptance corrected event yields may be determined through a χ^2 fit to the number of observed signal events found in each four-dimensional bin defined in terms of the submasses:[‡] (K^+K^-), $(\pi^+\pi^-)$, $(K^-\pi^+)$, and $(K^+\pi^-)$. In the absence of interference between the decay modes, the number of predicted signal events in each bin would be a linear transformation T of the fit parameters (which are the acceptance corrected event yields). Since the fit is linear the fit parameters can in turn be expressed as a linear transformation R of the observed bin populations. This R matrix, which multiplies a column vector of observed bin populations to produce a column vector of acceptance corrected yields for the decay modes, is constructed using the T matrix which is computed from Monte Carlo[§].

It can be shown that an equivalent procedure, which we apply here, is to create sepa-

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[‡]We have selected these submasses to correspond to those in which the resonances we are considering would peak if present. This results in 16 independent four-dimensional bins, where each dimension is partitioned into the two choices of being inside (within $\pm\Gamma$ where the natural width Γ is taken from the PDG [6]) or outside of the resonance peak. To allow for detector resolution, the invariant mass M_{KK} for the ϕ signal region was defined as $1.011 < M_{KK} < 1.027 \quad GeV/c^2$.

[§]In our Monte Carlo we have simulated the $D^0 \to VV$ modes assuming each step in the decay chain proceeds according to phase space.

rate $K^+K^-\pi^+\pi^-$ invariant mass histograms for each decay mode in which the events are weighted by the appropriate R matrix element** and determine the acceptance corrected yield by fitting the distribution to a Gaussian function for the signal over a linear background. Using Monte Carlo simulated mixtures of these seven decay modes we verified that biases in the corrected yields determined by this procedure are much smaller than the reported statistical errors and that the results are not sensitive to variations in reasonable choices for the resonance peak regions. To distinguish the $\overline{K^{*0}}K^+\pi^-$ and $K^{*0}K^-\pi^+$ decay modes would require using only D^*-tagged events in which the flavor of the neutral D is tagged by the charge of the pion in the decay $D^{*\pm} \to D^0\pi^\pm$. To avoid a reduction in the sample statistics we consider the two decay modes together.

The final results (expressed as acceptance corrected yields) are summarized in Table II and the six weighted histograms with fits superimposed are shown in Fig.2. The 7^{th} histogram (Fig.2f), which is the sum of all the modes combined, is equivalent to the $2K2\pi$ mass distribution (see Fig.1b) after correction for efficiency. The overall fit quality is evaluated by comparing the predicted signal yields in each of the submass bins with the observed signal yields, as shown in Fig.3. The calculated χ^2 is 5.5 (9 degrees of freedom) for a confidence level of 79%.

We calculated the relative branching ratios by dividing the acceptance corrected yields of Table II by the corrected yield (318218 ± 7408) for the normalizing decay mode $D^0 \to K^-\pi^+\pi^+\pi^-$. Our results are summarized and compared to other recent measurements in Table III. In our analysis we have distinguished between the two decay modes $D^0 \to \phi\pi^+\pi^-$ 3-body and $D^0 \to \phi\rho^0$. We can combine these two decay modes (using the sum of the histograms shown in Fig.2b and Fig.2c) to obtain the inclusive relative branching ratio measurement $\Gamma(D^0 \to \phi\pi^+\pi^-)/\Gamma(D^0 \to K^-\pi^+\pi^+\pi^-) = 0.011 \pm 0.003$. This result can be

**The weight is the R matrix element having a row number corresponding to the decay mode and column number given by the submass bin.

compared to measurements from E691 [9] ($0.0076^{+0.0066}_{-0.0049}$) and ARGUS [8] ($0.020 \pm 0.006 \pm 0.005$)[††]. Our measurement of the relative branching ratio for $D^0 \rightarrow \phi\rho^0$, as well as our inclusive measurement for $D^0 \rightarrow \phi\pi^+\pi^-$, are significantly lower than the ARGUS and CLEO determinations for $D^0 \rightarrow \phi\rho^0$. To further check our results we estimated the number of ϕ events from the D^0 signal by fitting the sideband subtracted K^+K^- invariant mass plot (see Fig.4) to a Breit-Wigner function convoluted with a Gaussian for detector resolution[‡‡]. The yield from the fit (31 ± 13 events) combined with detector efficiency indicates that the fraction of $D^0 \rightarrow K^-K^+\pi^+\pi^-$ events containing a ϕ is $13.2 \pm 5.8\%$, which is in good agreement with our resonant fit result of $15.5 \pm 5.0\%$ (calculated using the relative branching ratio measurement for $D^0 \rightarrow \phi\pi^+\pi^-$ and that for $D^0 \rightarrow K^-K^+\pi^+\pi^-$ from Table I). From our measurement of $\Gamma(D^0 \rightarrow \phi\rho^0)/\Gamma(D^0 \rightarrow K^-\pi^+\pi^+\pi^-)$ and the PDG [6] value for $BR(D^0 \rightarrow K^-\pi^+\pi^+\pi^-) = 8.1 \pm 0.5\%$, we derive $BR(D^0 \rightarrow \phi\rho^0) = 0.041 \pm 0.025\%$ which is consistent with the prediction of 0.022% from Bedaque, Das and Mathur [2], while it is 1.8σ below the BSW [3] prediction of 0.086% [§§].

Analogously to our analysis for the $D^0 \rightarrow \phi\pi^+\pi^-$ decay mode, we calculate the $D^0 \rightarrow K^{*0}K^-\pi^+ + c.c.$ inclusive relative branching ratio by combining[***] the decay modes $D^0 \rightarrow K^{*0}K^-\pi^+$ 3-body $+c.c.$ and $D^0 \rightarrow K^{*0}\overline{K^{*0}}$. Our mesurement $\Gamma(D^0 \rightarrow K^{*0}K^-\pi^+ + c.c.)/\Gamma(D^0 \rightarrow K^-\pi^+\pi^+\pi^-) = 0.027 \pm 0.007$ is lower than the ARGUS

[††]The ARGUS collaboration found the $\pi^+\pi^-$ invariant mass spectrum from the decay $D^0 \rightarrow \phi\pi^+\pi^-$ consistent with an entirely dominated ρ^0 contribution.

[‡‡]The D^0 mass signal region was defined as $1.850 < M < 1.878\ GeV/c^2$, that is $\pm 2\sigma$ about the nominal mass where $\sigma = 7\ MeV/c^2$ is the detector resolution for this state.

[§§]This value is calculated using $a_2 = -0.50$ derived from the latest D branching ratio and lifetime measurements [6].

[***]The efficiency corrected yield is determined by fitting the sum of histograms for $D^0 \rightarrow K^{*0}K^-\pi^+$ 3-body $+c.c.$ (Fig.2e) and twice that for $D^0 \rightarrow K^{*0}\overline{K^{*0}}$ (Fig.2f).

result[†††] of 0.066.

The present analysis is not well suited for measurement of the resonant substructure in the $D^0 \to \pi^-\pi^+\pi^-\pi^+$ decay. Since the possible decay modes include those containing broad resonances, for example $D^0 \to a_1^\pm \pi^\mp$, $a_1^\pm \to \rho^0\pi^\pm$, combined with the necessary Bose symmetrization of the decay amplitude, a more formal coherent amplitude analysis which additionally exploits the angular correlations in the decay products would be necessary.

In conclusion, we have measured the relative branching ratios of D^0 mesons into the $\pi^-\pi^+\pi^-\pi^+$ and $K^-K^+\pi^-\pi^+$ final states and have presented the first evidence of the decay mode $D^0 \to K^-K^+K^-\pi^+$. Our analysis of the resonant substructure in the decay $D^0 \to K^-K^+\pi^-\pi^+$ yields a significantly lower D^0 branching ratio into the modes containing a ϕ than previous experiments, while our relative branching ratio measurement for the $D^0 \to \overline{K^{*0}}K^{*0}$ channel, being much larger than predicted by the model of Bedaque, Das and Mathur [2], underscores the difficulty in accomodating FSI in charm meson decay. Our determination of the four-body branching ratio $\Gamma(D^0 \to K^-K^+\pi^-\pi^+)/\Gamma(D^0 \to \pi^-\pi^+\pi^-\pi^+) = 0.37 \pm 0.05 \pm 0.02$ can be compared with our previous determination of the two-body branching ratio $\Gamma(D^0 \to K^-K^+)/\Gamma(D^0 \to \pi^-\pi^+) = 2.53 \pm 0.46 \pm 0.19$ [12] where the K^-K^+ final state is dominant. The opposite behaviour of these two different multiplicity decay channels and the results of the resonance substructure analysis for the $D^0 \to K^-K^+\pi^-\pi^+$ mode support the importance of complex processes at the hadronic final state level.

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[†††]For comparison we have summed the ARGUS [8] measurements $\Gamma(D^0 \to K^{*0}K^-\pi^+)/\Gamma(D^0 \to K^-\pi^+\pi^+\pi^-) = 0.043 \pm 0.014 \pm 0.009$ and $\Gamma(D^0 \to \overline{K^{*0}}K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+\pi^+\pi^-) = 0.023 \pm 0.013 \pm 0.009$.

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TABLES

TABLE I. Branching ratios for $\Gamma(D^0 \to \text{Decay Mode})/\Gamma(D^0 \to K^-\pi^+\pi^+\pi^-)$ and comparison to previous experiments.

	$D^0 \to \pi^-\pi^+\pi^-\pi^+$	$D^0 \to K^-K^+\pi^-\pi^+$	$D^0 \to K^-K^+K^-\pi^+$
E687 (This work)	$0.095 \pm 0.007 \pm 0.002$	$0.035 \pm 0.004 \pm 0.002$	$0.0028 \pm 0.0007 \pm 0.0001$
ARGUS [8]		$0.041 \pm 0.007 \pm 0.005$	
CLEO [10]	0.102 ± 0.013	0.0314 ± 0.010	
E691 [9]	$0.096 \pm 0.018 \pm 0.007$	$0.028^{+0.008}_{-0.007}$	
WA82 [11]	$0.115 \pm 0.023 \pm 0.016$		
E687(1987-1988) [5]	$0.108 \pm 0.024 \pm 0.008$		

TABLE II. Corrected yields and fractions relative to the inclusive mode for the resonance substructure of the $D^0 \to K^+K^-\pi^+\pi^-$ decay mode. These values have not been corrected for branching ratios into unobserved decay modes of the intermediate resonances.

Decay Mode	Corrected Yield	Fraction
$(K^-K^+\pi^-\pi^+)_{NR}$	1525 ± 1492	0.14 ± 0.13
$\phi\pi^-\pi^+$ 3-body	427 ± 392	0.04 ± 0.04
$\phi\rho^0$	786 ± 481	0.07 ± 0.04
$K^-K^+\rho^0$ 3-body	3967 ± 833	0.36 ± 0.09
$K^{\star 0}K^-\pi^+$ 3-body $+c.c.$	399 ± 1972	0.04 ± 0.18
$\overline{K^{\star 0}}K^{\star 0}$	2325 ± 913	0.21 ± 0.09
Inclusive $K^-K^+\pi^-\pi^+$	11140 ± 1266	1.

TABLE III. Branching ratios for $\Gamma(D^0 \rightarrow \text{Decay Mode})/\Gamma(D^0 \rightarrow K^-\pi^+\pi^+\pi^-)$ and comparison to previous experiments. The branching ratios for the unseen decay modes of intermediate resonances have been included where appropriate.

Decay Mode	E687 (This work)	E691 [9]	CLEO [10]
$(K^-K^+\pi^-\pi^+)_{NR}$	< 0.011 (90% $C.L.$)	$0.001^{+0.011}_{-0.001}$	
$\phi\pi^-\pi^+$ 3-body	< 0.006 (90% $C.L.$)		
$\phi\rho^0$	0.005 ± 0.003		0.024 ± 0.006
$K^-K^+\rho^0$ 3-body	0.012 ± 0.003		
$K^{\star 0}K^-\pi^+$ 3-body $+c.c.$	< 0.017 (90% $C.L.$)	$0.010^{+0.016}_{-0.010}$	
$\overline{K^{\star 0}}K^{\star 0}$	0.016 ± 0.006	$0.036^{+0.020}_{-0.016}$	< 0.033 (90% $C.L.$)

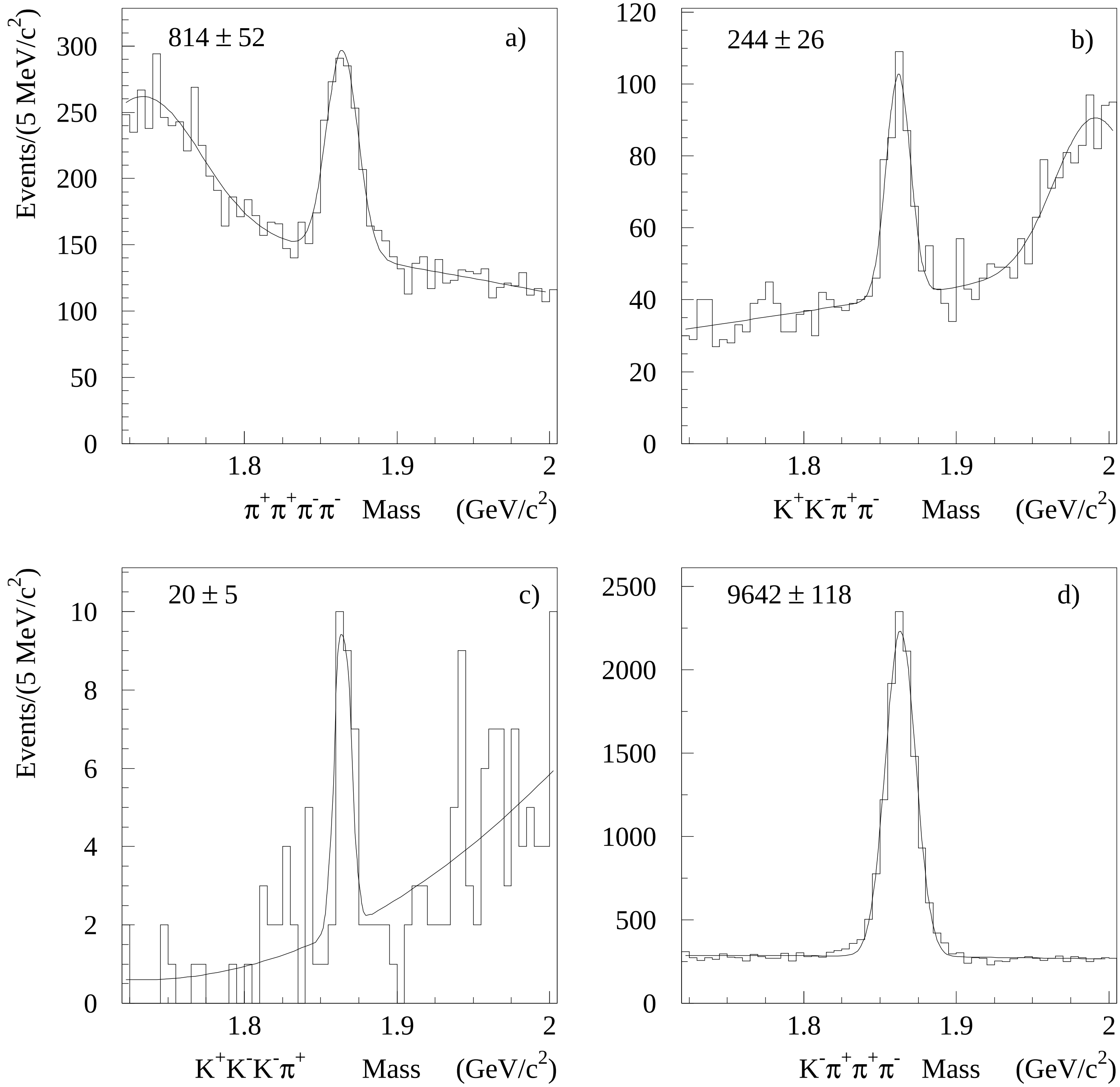

Fig. 1: (a) 4π invariant mass distribution. (b) $2K2\pi$ invariant mass distribution. (c) $3K\pi$ invariant mass distribution. (d) $K3\pi$ invariant mass distribution. The fits (solid curves) are described in the text and the numbers quoted are the yields.

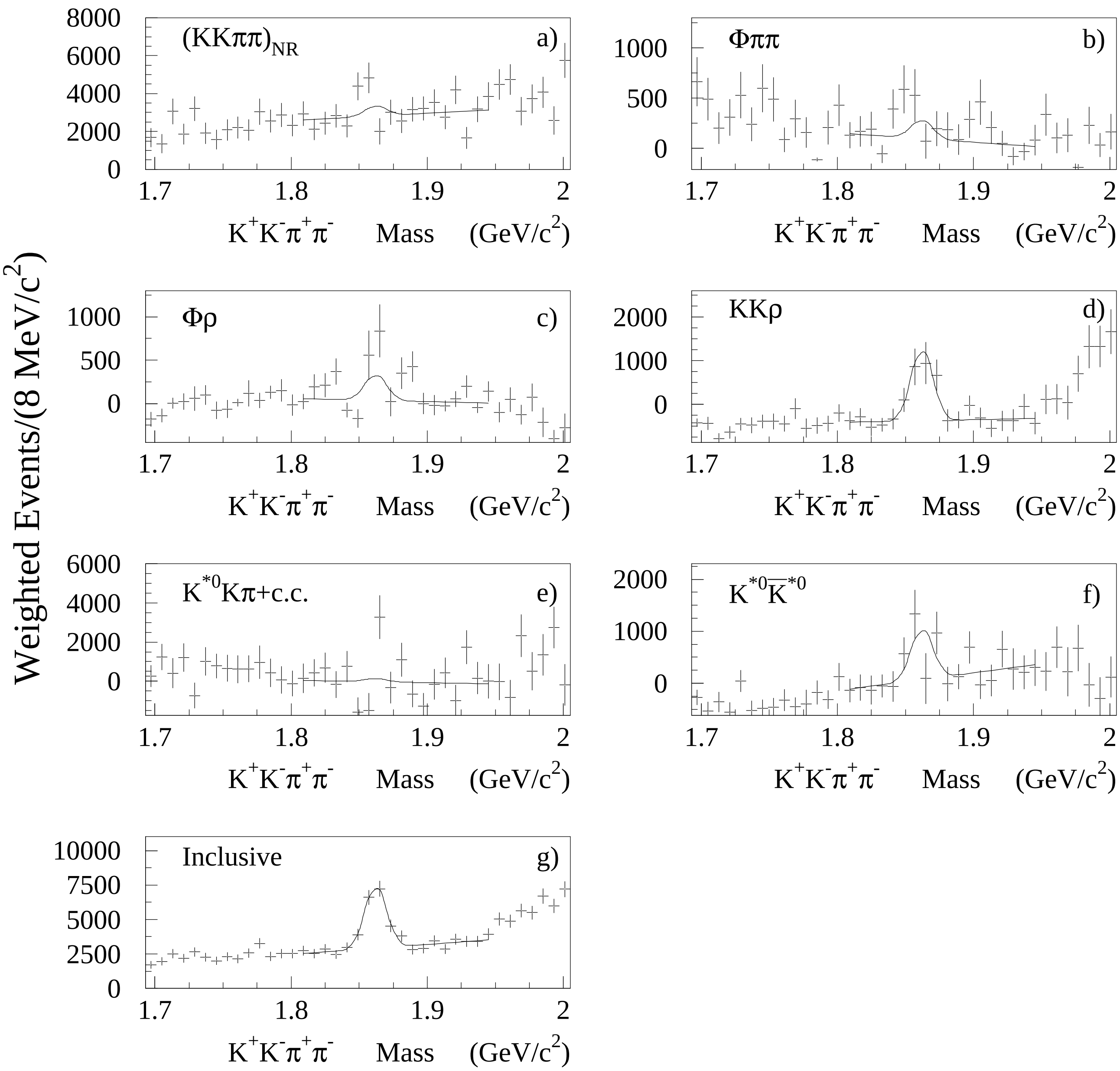

Fig. 2: $K^+K^-\pi^+\pi^-$invariant mass for (a) $(K^+K^-\pi^+\pi^-)_{NR}$ decay mode, (b) $\phi\pi^+\pi^-$ 3-body decay mode, (c) $\phi\rho^0$ decay mode, (d) $K^+K^-\rho^0$ 3-body decay mode, (e) $K^{*0}K^-\pi^+$ 3-body $+c.c.$ decay mode, (f) $\overline{K^{*0}}K^{*0}$ decay mode, (g) Inclusive : sum of all the 6 modes. The fits (solid curves) are to a Gaussian for the signal over a linear background.

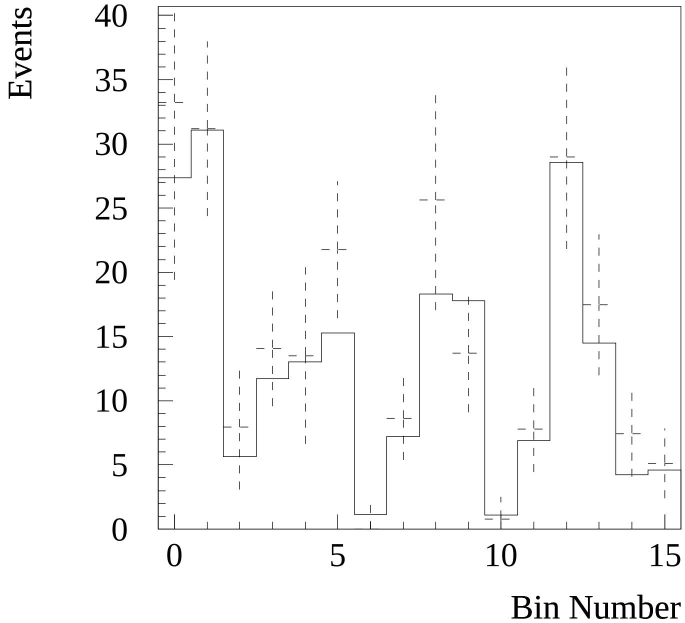

Fig. 3: The solid histogram is the signal yield predicted by the fit while the dashed points are the observed signal yields in each of the 16 submass bins. The submass bins are defined by numbers η which have the value 1 (0) if the submass is within (outside) a resonance peak region, according to the mapping: bin number $= 1\eta_{\pi^+\pi^-} + 2\eta_{K^+K^-} + 4\eta_{K^+\pi^-} + 8\eta_{K^-\pi^+}$.

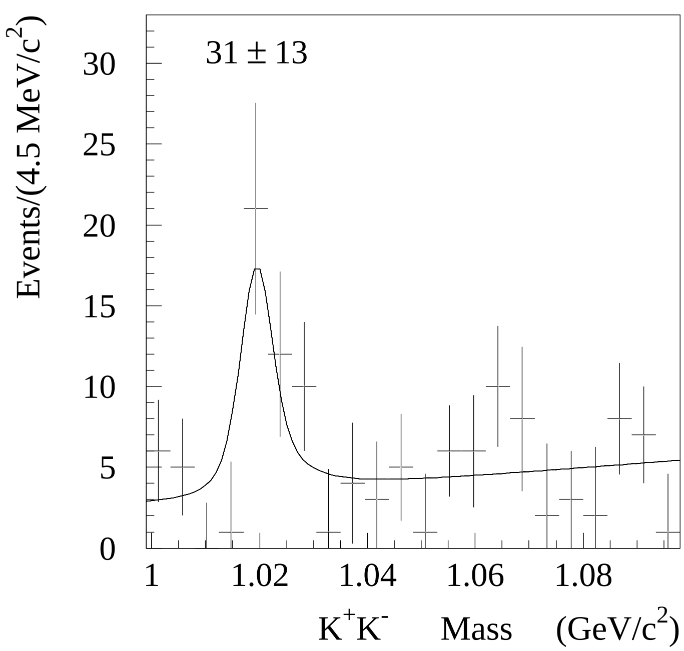

Fig. 4: KK invariant mass distribution. The fit (solid curve) is to a Breit-Wigner function convoluted with a Gaussian for detector resolution over a second degree polynomial for the background.